Aero acoustics of a flow pipe having a single small cavity

Daniel Mazzoni, U. Kristiansen

Forum Acusticum 2011 - Aalborg - Denmark

Aero acoustics of a flow pipe having a single small cavity

Daniel Mazzoni
Laboratoire de Mecanique et d'Acoustique, UPR CNRS 7051, 31 chemin Joseph-Aiguier, 13402 Marseille Cedex 20, France

Ulf Kristiansen
Acoustics Research center, NTNU, O.S. Bragstads plass 2b, 7491 Trondheim, Norway.

Summary
The whistling of a pipe-cavity system subjected to an internal flow of fluid is considered in this paper. This phenomenon consists in a self-sustained oscillation in the shear layer that develops at the interface between the fluid flow in the pipe and fluid in the cavity. Some basic geometrical relations regarding the sound emission are considered : the cavity length, and the distance between the air inlet and the cavity. The tested pipes had lengths between 0.65m and 1.459m, and all the diameter 42mm. The maximum velocity was 30m/s. A noise reduction experiment is also presented that involves a time harmonic sound superposed on the whistling noise.

PACS no. 43.20.Ks, 43.28.Ra

1. Introduction

Unstable flows can be important noise sources or form the basis of musical instruments. A classic system is the circular cylinder in a cross flow where Aeolian tones are generated by regular vortex shedding. A system involving an unstable flow and an acoustic cavity is the so-called Helmholtz resonator, which will produce pure tones when exposed to airflow.

In this presentation we present results from measurements on another simple and well defined aeroacoustic system: a small cavity at the end of a cylindrical pipe. In the simplest case, the system consists of two oscillators, the shear layer above the cavity, and an acoustic mode in the pipe. In our investigation we have concentrated on the lower modes of the pipes; the acoustic wavelengths are in all cases much longer than the cavity dimensions. With the influence of sound, the shear layers above the cavities are expected to behave in a modal fashion. These modes might be described by wave lengths of the shear layer corresponding to the cavity length, or, as is found when the shear layers are exposed to strong acoustic fields and curl up into separate vortices: numbers of vortices crossing the cavity span at the same time [2].

In part 2 we present results from an investigation on the influence of cavity length on a specific configuration. In part 3 we give an example on how a modal tone generated by the flow might be strongly influenced by an added acoustic signal from an external loudspeaker. Finally, in part 4, we have investigated the influence of the smooth pipe length upstream of the cavity.

2. Influence of the cavity length on the behavior of a whistling pipe

In this section we focus on the acoustic response of the pipe-cavity system as a function of the stream-wise length of the cavity.

The experimental system is presented in figure 1: A pipe-cavity system is located on the upstream side of a box with a 32cm by 32cm square section and 60cm long. Downstream of this box we use a vacuum pump to create a flow of air. The box contains a loudspeaker located in front of the air outlet section of the pipe: This loudspeaker will be used in the next section to create an acoustic wave traveling along the pipe-cavity system. A radial cavity of depth 5mm and variable length L_c in the stream-wise direction is inserted in the wall of the pipe. The upstream edge of this cavity is located at 5mm from the air inlet. The stream-wise cavity length L_c can vary continuously from 0 to 20mm. Let us denote by L_p the length of the pipe when the cavity is absent ($L_c = 0$), $D = 4.2$cm the inside diameter of the pipe, U_0 is the flow speed measured by a thermal velocimeter at the center of the pipe. In our experimental system, the flow speed

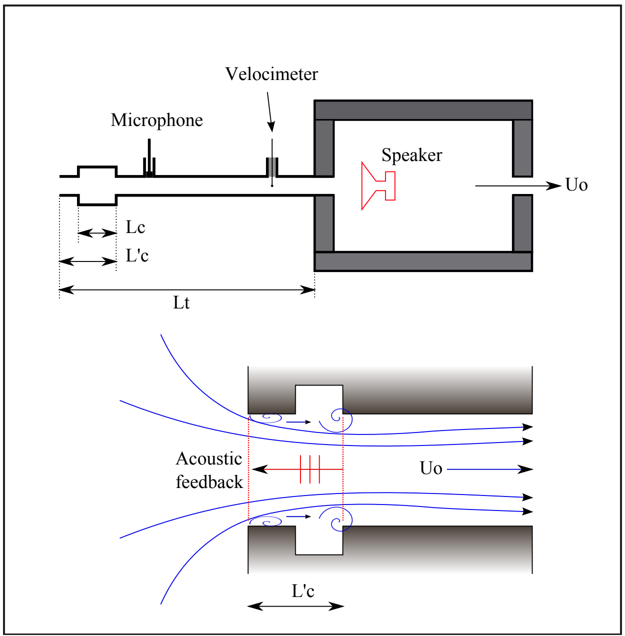

Figure 1. Experimental system

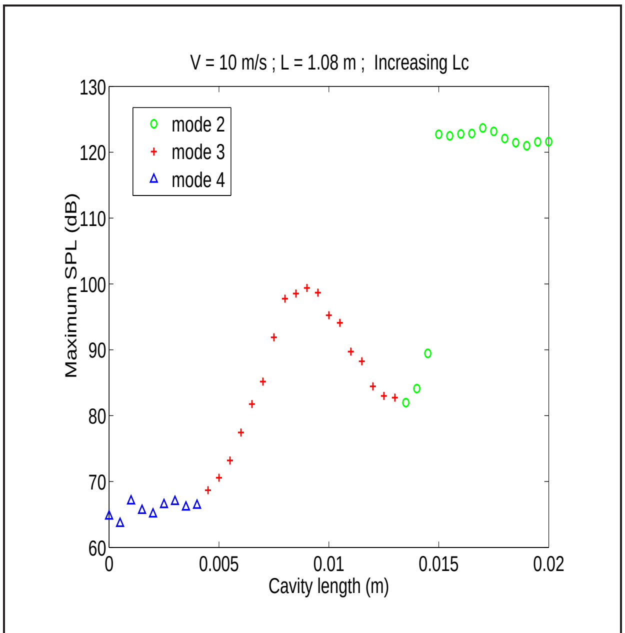

Figure 2. Maximum SPL measured in the pipe 1cm from the air inlet as a function of the cavity length

can vary from 0 to 30 m/s. The acoustic pressure is measured inside the pipe by a thin B&K microphone sonde located 1cm from the air inlet. The eigenfrequencies ν_n of this pipe of are given by:

$$\nu_n = c/(2 * (L_t + 0.8 * D)) \qquad n = 1, 2, 3, ...(1)$$

where $c = 343\text{m/s}$ is the speed of sound, and n the acoustic mode number.

The figure 2 is obtained by measuring the maximum sound pressure level in a pipe 1.08m long. It

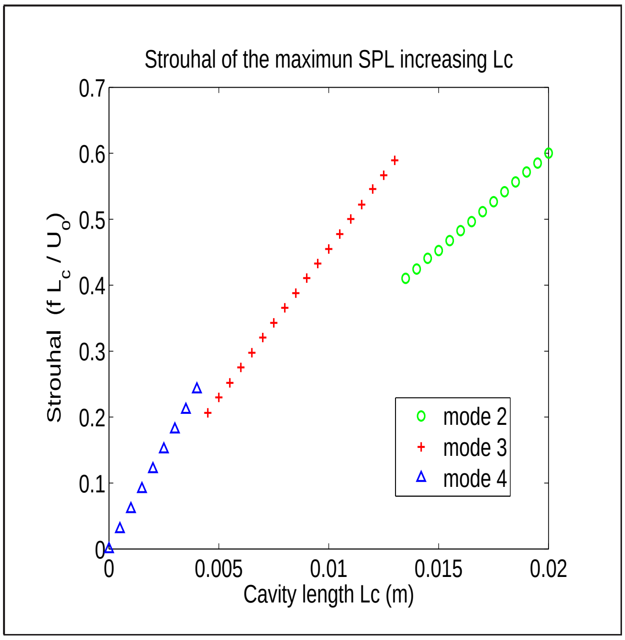

Figure 3. Strouhal number measured in the pipe 1cm from the air inlet as a function of the cavity length

was measured in the pipe 1cm from the air inlet. for a flow speed $U_0 = 10\text{m/s}$, when the cavity length vary from 0 to 20mm. The figure 2 shows that the whistling phenomenon start when the cavity in approximately 5mm long: for $5\text{mm} < L_c < 12\text{mm}$ the third acoustic mode of the pipe is excited. For $L_c > 12\text{mm}$ the pipe responds on it's second acoustic mode. Each acoustic mode of the pipe (modes 2,3,4) is excited over a range of cavity lengths. The same behavior is presented by Erdem & al. in [3] when increasing the speed of the flow: the cavity modes of the pipe are excited by multiple ranges of flow speeds.

For the same experiment as presented in figure 2, Figure 3 presents the Strouhal number based upon the cavity length fL_c/U_0 plotted as a function of the cavity length L_c. The figure 3 presents 3 segments with constant slope f/U_0, the jumps between these segments represent a change of the acoustic mode of the pipe. consideration

3. Influence of an acoustic wave on the whistling pipe

The sound attenuation in whistling flow pipes is still challenging: In [3] the authors propose a reduction method based on differences in the length of the inlet and of the outlet of the pipes. In [4] the authors use a compression driver channeled to the cavity leading edge to reduce the cavity flow tone. In [5] a loudspeaker is used to perform noise attenuation in a corrugated pipe. In a very similar experiment presented by [5], we use in this paper a loudspeaker located in front of the air outlet section of the pipe (see figure 1) to create a tonal acoustic wave traveling in the

Table I. Table giving the details of pipes and cavity length.

	L_p	L_c	$L_t = L_p + L_c$	U_0
figure 2	1.08m	0 to 20mm	1.08m $< L_t <$ 1.1m	10m/s
figure 3	1.08m	0 to 20mm	1.08m $< L_t <$ 1.1m	10m/s
figure 4	1.451m	8mm	1.459m	11.5m/s

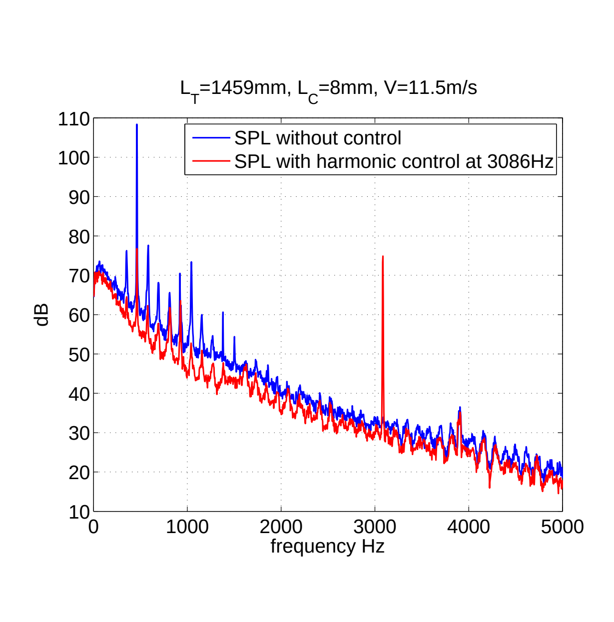

Figure 4. Addition of an harmonic sound at frequency 3086 Hz to the singing pipe: SPL vs frequency measured at 13cm from the air inlet

pipe. Varying the frequency and the amplitude of this tonal wave, we measure the acoustic pressure when the pipe is excited by the flow in a whistling speed region. For this experiment, we use a pipe of total length $L_t = 1.459$m and a cavity of length $L_c = 8$mm excited at $U_0 = 11.5$m/s. The sound pressure level is measured on a microphone wall mounted in the pipe at 13cm from the air inlet (see figure 1).

The results are presented on figure 4: the blue curve is the sound pressure level measured at $U_0 = 11.5$m/s. A whistling tone sound with a maximum sound pressure level of 108dB at the frequency 462Hz can be observed. This tonal sound correspond to the fourth eigenmode of the pipe. The red curve is the sound pressure level measured on the same microphone when an harmonic control sound is generated by the loudspeaker at the frequency 3086Hz : the amplitude of this control sound is determined empirically by tuning the amplifier in order to observe the flow tone noise and the control noise at approximately the same levels. On the red curve, one can see that the flow tone noise of the whistling pipe has been reduced from 108dB to 76dB. Similar results are presented by [4] for a different geometry : a cavity flow tone noise controlled by a compression driver.

4. Influence of pipe length upstream of cavity

Some measurements were done to see what influence the smooth pipe section upstream of the cavity would have on the generated tones. For these tests, the cavity length was kept constant at 10mm at the end of a 645mm long pipe.

4.1. 10mm long cavity with 15mm and 40mm upstream sections

Some initial testing demonstrated that the pipe would not sing (for velocities up to $U_0 = 26$ m/s) if the smooth upstream pipe length was shorter than 5mm or longer than 40mm, that is, $5mm \leq L_{\text{upstream}} \leq 40mm$ was found to be a necessary condition for generating the pipe tones.

Figures 5 and 6 show results for two L_{upstream} configurations, 15mm and 40mm. The upper panel in each figure show the sound pressure level as a function of the axis flow velocity U_0. The sound pressures were measured 30cm in front of the tube's flow entry section, and 10cm off axis. In the lower panel is plotted the Strouhal number $(f \cdot L_{\text{cavity}}/U_0)$ against the velocity.

In figure 5 is seen that the tone generation starts at about 6.5m/s. The first tone generated corresponds to the first longitudinal pipe mode. With increasing velocity the tone first jumps to the third modal frequency, before it lowers to the second with even higher velocities. At the same time it is seen that the Strouhal numbers descend with increasing velocity for each mode.

For the pipe having a longer upstream section it is seen that the tone generation starts at about 9m/s with the first and second modes generated at low velocities. Between 12 and 16.5m/s there is no sound generation. The 3rd and 2nd modes are then generated before the system jumps to the 4th mode at the high velocities. It is again seen that the Strouhal numbers descend monotonically for each mode.

With the influence of sound, the shear layers above the cavities are expected to behave in a modal fashion. Assuming the hydrodynamic wave speed to be approximately equal to half the axis velocity, and assuming the cavity length equal to one half hydrodynamic wave length for the first hydrodynamic mode, the corresponding Strouhal number equals 0.25, [1]. Also, under the influence of strong acoustic fields, the shear layers are found to curl up into vortices. The

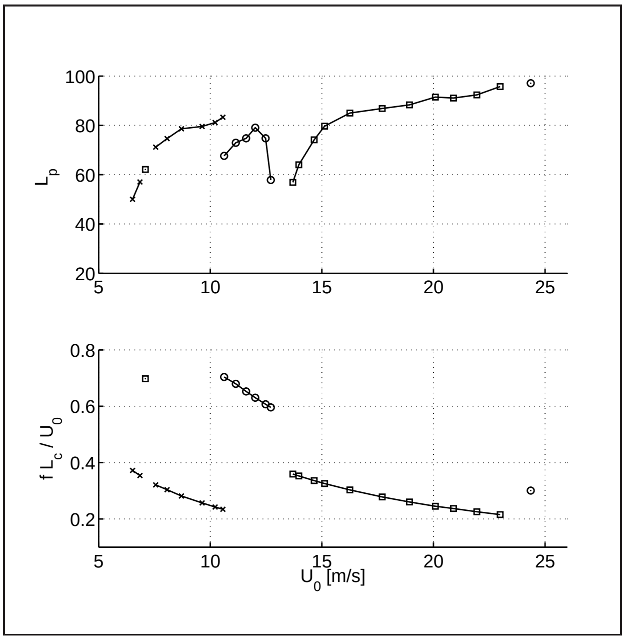

Figure 5. Sound pressure level and Strouhal number as function of U_0 for 10mm cavity having a 15mm upstream section. Mode 1(240Hz, cross), mode 2(485Hz, square), mode 3(715Hz, circle), mode 4(955Hz, star).

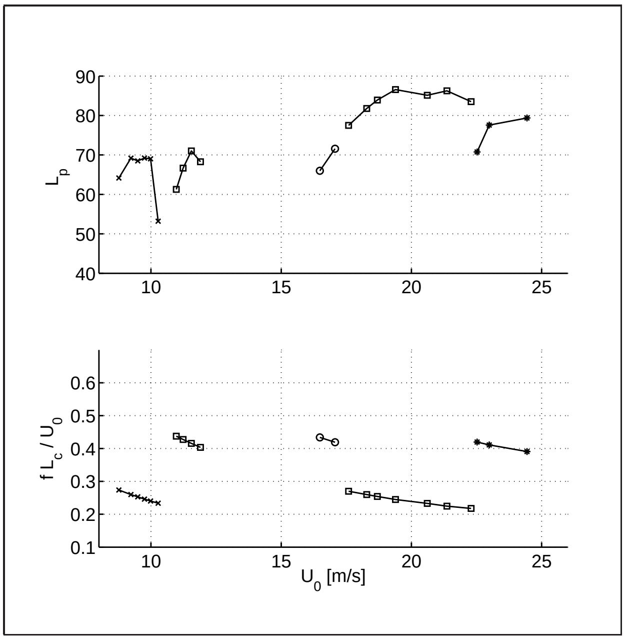

Figure 6. Sound pressure level and Strouhal number as function of U_0 for 10mm cavity having a 40mm upstream section.

hydrodynamic modes can then be understood as one, or more vortices passing the cavity length [2].

The Strouhal numbers in the present investigation are seen to fall into groups descending towards 0.2, 0.4, and 0.6. The hydrodynamic motion causing tonal generation is therefore indicated to represent one of the three lowest hydrodynamic modes.

In figure 7 we have plotted the sound pressure level along the axis going into the pipe about one half wavelength. This was done by moving a microphone sonde into the pipe. The different configurations are given in table II. The last column of this table gives the ratio of acoustic pressure at the downstream cavity section divided by the pressure measured at the first pressure antinode. From the figure it is seen that the antinodal pressure decreases with upstream pipe length and becomes more "noisy". It is also interesting to note that for the different situations presented, the cavity is located at very different locations along the first part of the standing wave.

Figure 5 was experimentally found by decreasing the velocities through the range. Around 11.5m/s the third mode was found to be stable. If the opposite procedure was chosen, *i.e.* increasing the velocities through the region, the first mode would be heard at the same velocity. It was observed that both situations were stable. It was however possible to go from the low tone to the high by giving the flow an impulse, like moving the hand across the inflow opening; and from the high tone to the low by singing a tone around 240Hz into the pipe opening! The two spectra are shown in figure 5.

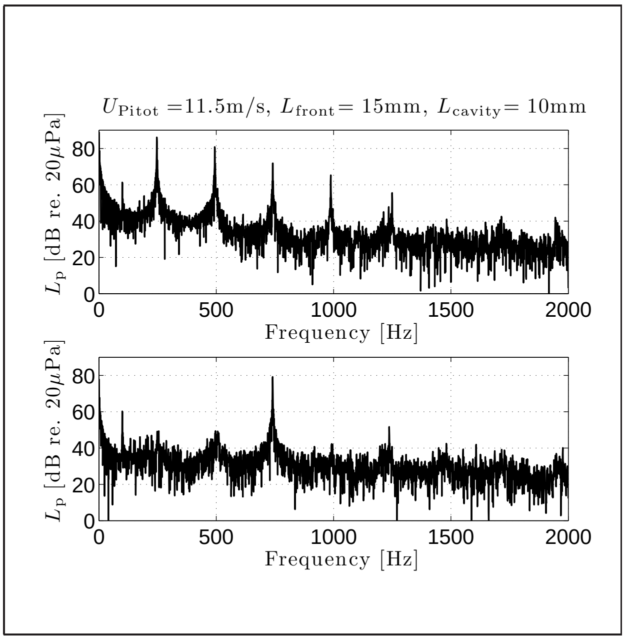

Figure 8. Two stable conditions measured for pipe "b"

5. CONCLUSIONS

It has been shown that a flow pipe having a single small cavity close to the opening will sound at relatively high sound pressure levels. For the pipe tested, it was shown that the cavity length, and the length of the smooth pipe section upstream of the cavity, have to be within certain limits. The Strouhal numbers calculated indicate that the sound generation involve the three lowest hydrodynamic modes of the shear layer above the cavity. It was also found that adding a pure

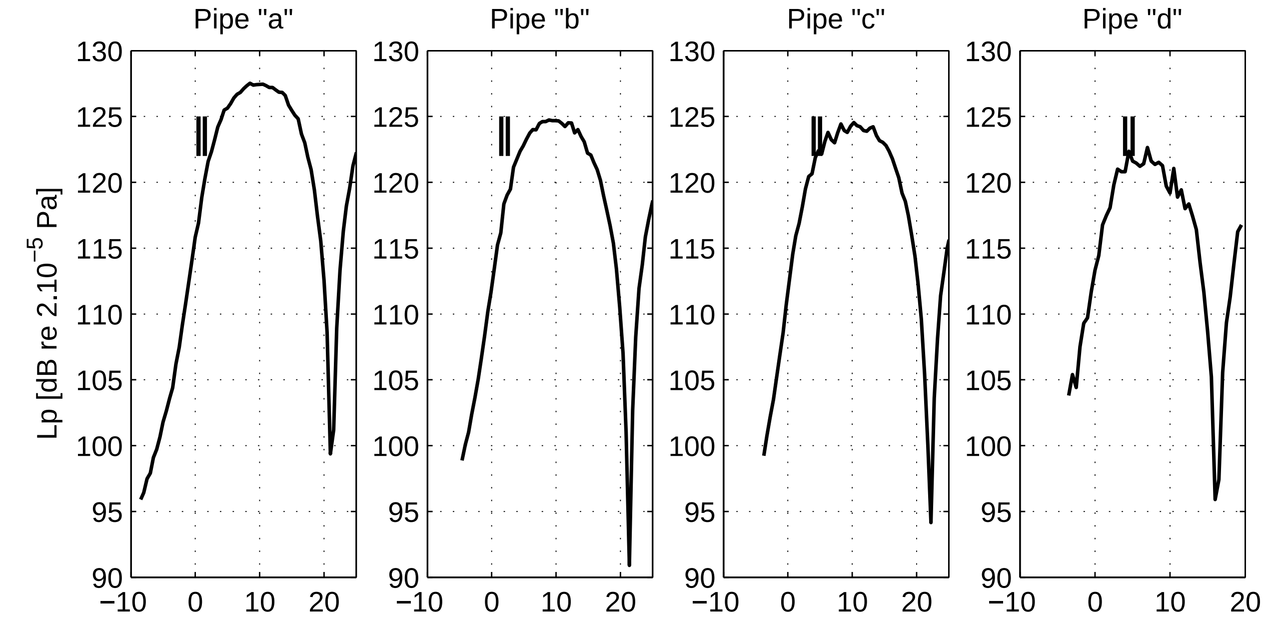

Figure 7. Sound pressure level measured into pipe along axis for 4 different geometries. x-axis is in cm. Position of cavity is marked with vertical lines.

Table II. Table giving the details of pipes tested in figure 3.

Pipe	U_0	L	L_{upstream}	L_{cavity}	*Frequency*	$p_{\text{cavity}}/p_{\text{max}}$
"a"	13.6 m/s	650mm	5mm	10mm	755 Hz	0.44
"b"	11.5	660	15	10	740	0.52
"c"	17.1	660	40	10	715	0.77
"d"	24.4	680	40	10	944	-

tone sound from a loudspeaker would reduce the flow generated tone considerably: a 32dB reduction of the whistling was observed in our experiment. As this might have practical applications, we plan to investigate this effect more systematically in the time to come.

References

[1] A. Chaigne and J. Kergomard: Acoustique des instruments de musique. Editions Belin 2008.

[2] D. Tonon and B.J. Landry and S.P.C. Belfroid and J.F.H. Willems and G.C.J. Hofmans and A. Hirschberg: Whistling of a pipe system with multiple side branches: Comparison with corrugated pipes. Journal of Sound and Vibration **329** 210, 1007-1024.

[3] D. Erdem, D. Rockwell, P. Oshkai, M. Pollack. Flow tones in a pipeline-cavity system: effect of pipe asymmetry. Journal of Fluids and Structures **17** (2003) 511-523.

[4] M. Debiasi, J. Little, E. Caraballo, X. Yuan, A. Serrani, J. H. Myatt, and M. Samimy. Influence of Stochastic Estimation on the Control of Subsonic Cavity Flow ? A Preliminary Study. AIAA Paper 2006-3492, 3rd AIAA Flow Control Conference, San Francisco, CA, June 2006.

[5] V.F. Kopiev, M.A. Mironov, V.S. Solntseva. Sound generation, amplification and absorption by air flow through waveguide with periodically corrugated boundary. Proc. Forum Acousticum, Budapest, 2005.